The Role of Digital Twins in Future Skill Development

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Abstract*. A digital twin is a virtual system designed to replicate the functionality of a physical object. The concept originating from the industrial sector offers promising avenues for creating immersive, interactive, and personalized learning experiences. This paper explores the potential applications of digital twin technology in the field of education. In order to ascertain the context and methodology of the use of digital twins in education, we present the findings of our literature analysis prepared using the PRISMA approach. Furthermore, we explore the opportunities associated with integrating digital twin technology into educational environments and propose future directions for research and development.*

Keywords. digital twin, education, enhancement

1 Introduction

Digital twins (DTs) have already been used for distance learning in several fields, including healthcare, tourism, and engineering education (Hawkinson, 2022). It is emphasized that COVID 19 technology has accelerated the adoption of digital twin technology (Hazrat et al., 2023). Namely, the emergence of the coronavirus pandemic forced professors and students to use distance learning methods to ensure continuous education (Itani et al., 2022).

The rise of the virtual world, or metaverse technology, has significantly enhanced pedagogical and technical support for education, expanding learning opportunities and demonstrating numerous benefits in distance learning (Tlili et al., 2022). According to EU Business School (2022), one of the most promising applications of the metaverse in education is the "gamification" of learning. This approach turns the classroom into a virtual world and encourages students to finish their assignments.

Digital twin technology can help incorporate the ideas and concepts of the natural or physical world in metaverse-based education, making education more realistic and user-friendly (Mitra, 2023).

Some of the benefits of introducing DT into the educational context are personalized learning, better collaboration possibilities and content accessibility (Hawkinson, 2022). It has been shown that blended learning can significantly improve students' motivation, interest and learning approach (Kartashova et al., 2024).

At the same time, it is emphasized that such education requires investment in professional development of educators to increase their ability to teach students (Hazrat et al., 2023).

The statistics of DT in education show that they will continue to gain popularity due to the shift to online learning that has occurred. According to the National Center for Education Statistics (NCES), the pandemic affected public colleges to enroll approximately 7.5 million online students in 2022 (U.S. Department of Education, 2023). In 2021, as in-person learning slowly returned, distance learning dropped to 59%. Even though online learning rates decreased slightly in 2022, they were still significantly higher than in the years prior to the pandemic (Hamilton and Beagle, 2024).

Moreover, it is also clear that investments in educational technologies have significantly increased. Between 2017 and 2021, US educational technology venture funding jumped from $1 billion to $8 billion, and this growth is anticipated to continue as more universities adopt blended learning and advanced technologies (HolonIQ's Education Intelligence Unit, 2022).

The metaverse is expected to transform cities, schools, and factories, resulting in a digital twin of everything. As a result, the impact of these changes on higher education could be fatal. The Pew Research Center (2023) predicts that 50% of US colleges could close due to outdated facilities and inability to adapt to new technologies. Though some faculties actively use DT in their teaching.

For example, Quanser's QLabs software has been used by 2500 academic institutions worldwide to allow engineering students to manipulate and test 3D models in a virtual environment (Quasner.com, n.d.). Such statistics show that digital technology is slowly being applied in education.

The aim of this paper is to discover the possible applications and advantages of using DT in an educational context.

To achieve this aim, two guiding questions drive this study:

- RQ1: What are domains/applications of DT usage in education?
- RQ2: What are the possible enhancements of introducing DT in education?

The rest of the paper is structured as follows: Section 2 explains the theoretical framework of DT; Section 3 outlines utilized research methodology; Section 4 presents the results about DT applications in education; Section 5 discusses findings about possible DT enhancements in learning environment; Section 6 outlines research gaps and future directions to address the research gaps; and Section 7 concludes the work.

2 Theoretical Framework

2.1 Definition and Conceptualization of Digital Twins

DTs are virtual representations of physical objects or systems that simulate their behavior and characteristics. The concept originated from NASA's Apollo program, where identical space vehicles were built for testing purposes (Liljaniemi & Paavilainen, 2020; Andreasyan and Balyakin, 2022). DT consist of two systems: a physical entity and a virtual model containing all relevant information about the physical system (Nikolaev et al., 2018). They are used in various sectors, offering benefits such as cost reduction, predictive maintenance, and improved time-to-market (Tjahyadi et al., 2023; Flaga & Pacholczak, 2022). DT leverage technologies like IoT, machine learning, and big data to enable seamless interaction between physical and digital domains, providing detailed insights for optimization and innovation (Andreasyan and Balyakin, 2022). In education, DT can include human factors, such as students and teachers, requiring specific considerations during development (Terkaj et al., 2024).

2.2 Key Components and Characteristics

DTs in education involve creating digital replicas of educational entities like students, teachers, and institutions, integrating human factors. Key components include generating digital copies of educational entities, data collection, and real-time data transmission (Liljaniemi & Paavilainen, 2020; Chamorro-Atalaya et al., 2024). Characteristics encompass the synchronization between physical and digital systems, visualization of system information, and integration of technologies like IoT and AI (Andreasyan and Balyakin, 2022). DTs enable simulations, virtual environments for testing, and data-driven applications, enhancing learning experiences by providing hands-on applications of ICT skills and exposure to Industry 4.0 technologies (Geuer et al., 2023; Acker et al., 2023). They offer opportunities for virtual experiments, preparation for real-world scenarios, and continuous data flow between physical objects and DT (Raudmäe et al., 2023; Orsolits et al., 2022), fostering a deeper understanding of complex concepts in a safe and interactive manner (Tjahyadi et al., 2023).

2.3 Types of Digital Twins

DT can be categorized into three main types: Digital Model, Digital Shadow, and Hybrid Digital Twins. The Digital Model represents a digital replica of a physical object without automated data exchange (Kim et al., 2018). On the other hand, the Digital Shadow involves an automated one-way data flow between physical and digital objects (Liljaniemi & Paavilainen, 2020). Hybrid DTs combine elements of both physical and cyber representations, allowing for bidirectional data exchange and synchronization between the physical entity and its digital counterpart (Andreasyan and Balyakin, 2022). These different types of DTs play crucial roles in various industries such as manufacturing, smart city development, and healthcare, offering benefits like predictive maintenance, improved efficiency, and enhanced decision-making capabilities (Lee et al., 2023).

3 Methodology

For a literature review, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) technique was utilized with defined eligibility criteria (Moher et al., 2009). The PRISMA procedure was used to identify publications related to DTs in education. The search was conducted using "digital twin" in titles, abstracts, and keywords and "education" included only in the title of the paper to narrow the search. All posters, book chapters, reports and reviews are excluded from the search, also excluding all publications not written in the English language. Final search results were obtained on April 10, 2024. A total of 116 papers were found in the initial search using the Scopus and WoS databases (69 from Wos and 47 from Scopus). Following the elimination of duplicates, a brief review of the titles and abstracts was conducted. As a result, 66 articles (29 from Wos and 37 from Scopus) that were relevant to the field of DT in education were chosen. After reading the paper in its entirety, 37 publications (19 from Wos and 18 from Scopus) that provided examples of usage DT in education with defined benefits were selected for analysis. To get the most recent data on their applications, the investigation only included English language publications that were released within the last three years, from 2022 to 2024.

4 Applications of DT in Education

Table 1 shows the areas and applications of DT, where most of them were observed specifically in STEM education (21 articles), online education (9 articles), vocational education (2 articles) and 1 article each for special cases were found in areas such as environmental education, sustainable education, IoT education, vocal music, and physical education.

Table 1. Main areas and applications of DT in education

No.	Author	Area	Application
1.	Chamorro-Atalaya et al. (2024)	STEM education	DT in higher education for engineering training and simulation-based training.
2.	Hagedorn et al. (2023)	STEM education	DT for project-based learning in engineering.
3.	Acker et al. (2023)	STEM education	Low-cost DT for teaching robotics (Industry 4.0).
4.	Raudmäe et al. (2023)	STEM education	DT for omnidirectional mobile robot platform.
5.	Zangl et al. (2023)	STEM education	DT for measurements in robotics and AI.
6.	Čech and Vosáhlo (2022)	STEM education	DT to enhance control education affordability.
7.	Tjahyadi et al. (2023)	STEM education	Digital twin-based laboratory for control engineering.
8.	Bunse et al. (2022)	STEM education	Distance laboratory courses in engineering education.
9.	Boettcher et al. (2023)	STEM education	DT for laboratory experiments in engineering.
10.	Christopoulos et al. (2022)	STEM education	DT and virtual reality in robotics education.
11.	Kandasamy et al. (2022)	STEM education	DT for cyber security testing, research and education.
12.	Orsolits et al. (2022)	STEM education	DT to facilitate mixed reality-based robotics.
13.	Samak et al. (2023)	STEM education	DT to support simulation for autonomous vehicles.
14.	Hazrat et al. (2023)	STEM education	Enhance engineering education through Industry 4.0.
15.	Mathur (2023)	STEM education	DT to support cybersecurity research, education, and training for preserving critical infrastructure.
16.	Peshkova et al. (2023)	STEM education	Digital twin usage in medical education.
17.	Goppold et al. (2022)	STEM education	DT for visualizing error consequences in health.
18.	Rovati et al. (2024)	STEM education	Developing a patient DT for critical care education.
19.	Gary et al. (2023)	STEM education	DT in critical care training.
20.	Geuer et al. (2023)	STEM education	Designing smart photometry in Education 4.0.
21.	Lee et al. (2023)	STEM education	DT in math education (enhance gamified learning).
22.	She et al. (2023)	Online education	DT for enhancing credit management in education.
23.	Mourtzis et al. (2023)	Online education	DT hybrid model for personalized education 4.0.
24.	Andreasyan and Balyakin (2022)	Online education	Implementing DT technology in educational practices (application of education digitalization).
25.	Hsiao et al. (2022)	Online education	DT to support real-time expert feedback.
26.	Rubtsova et al. (2021)	Online education	DT for optimizing learning effectiveness.
27.	Dhananjaya et al. (2024)	Online education	Digital recommendation system for personalized learning in online education.
28.	Mitra (2023)	Online education	DT for innovative metaverse-based education.
29.	Xi and Cong (2022)	Online education	DT like a virtual tour in survey education.
30.	Flaga and Pacholczak (2022)	Online education	DT for education and training purposes (bridge real and virtual worlds).
31.	Eriksson et al. (2022)	Vocational education	Applying DT in higher education (example of industrial-like laboratories).
32.	Vrysouli et al. (2022)	Vocational education	DT to enhance vocational education in construction (sustainability and architectural design).
33.	Ruppert et al. (2022)	IoT education	DT of the laboratory (education for Industry 5.0).
34.	Komninos and Tsigkas (2022)	Environmental education	Prototyping DT system (combining smart birdhouse and an electronic DT).
35.	Georgakopoulos et al. (2023)	Sustainable education	Remote lab courses for distance education (designed on the sustainable development principles).
36.	Intelligence (2023)	Vocal Music Education	Application of the DTs platform for music education in higher institutions.
37.	Liu and Jiang (2022)	Physical Education	DT to improve somatosensory recognition efficiency (visual sensing training system).

5 Enhancements of Introducing DT

This chapter will highlight five categories in which DT is believed to contribute to enhancement when utilized in the educational process.

5.1 STEM Education

By 2030, higher education is expected to undergo substantial changes. Launching DT will improve learning effectiveness and open up new research options (Rubtsova et al., 2022). Increased robot use in industrial production necessitates adaptation of education programs. Combining immersive technologies like mixed reality with robotics education offers promising opportunities for expanding knowledge (Orsolits et al., 2022). The use of digital twin technologies can motivate students to study and improve learning outcomes (She et al., 2023). In STEM education, a portable photometric measurement device called the Smart Education Photometer (SmaEPho) designed for inquiry-based learning, overcomes the challenges of limited budgets in purchasing professional photometric measurement systems (Geuer et al., 2023). This makes it easier for students to learn about electrical circuits and photometry, allowing them to test and build circuits while lecturers use DT as a demonstrator.

Furthermore, online learning feature analysis technology improves online education management by integrating students' cognitive data and teachers' resources (Intelligence, 2023). Christopoulos et al. (2022) are proposing an approach which can be utilized to teach robotics in blended learning scenarios. The networked virtual world accurately represents laboratory robots and tools, whereas the digital twin system simulates actions that occur in the physical laboratory.

5.2 Virtual Laboratories and Simulations

Virtual labs are extensively used in chemistry, physics, biology, environmental science, and medical education to simulate experiments that may be too dangerous, expensive, or time-consuming to perform in a traditional lab setting (Geuer et al., 2023; Mourtzis et al., 2023; Gary et al., 2023). In medical education, DT can be used to create a database of data that will help in further research of diseases analysis (Peshkova et al., 2023). The use of digital twins in engineering education provides a safe environment for students to explore the behavior of complex machinery and control systems without the need for physical prototypes (Chamorro-Atalaya et al., 2024; Acker et al., 2023; Andreasyan and Balyakin, 2022; Dhananjaya et al., 2024; Samak et al., 2023; Terkaj et al., 2024; Tjahyadi et al., 2023). Chamorro-Atalaya et al (2024) further described simulations based on DT as advanced interactive learning environments in engineering disciplines allowing students to virtually replicate laboratory equipment or practical teaching stations (Mourtzis et al., 2023; Samak et al., 2023; Andreasyan and Balyakin, 2022; Dhananjaya et al., 2024). Virtual simulations are crucial in medical education (Chamorro-Atalaya et al., 2024) for providing a risk-free environment for students to practice surgical procedures, patient care, and diagnostic skills (Hagedorn et al., 2023; Rovati et al., 2024). Modeling using tools like Simscape in a DT based laboratory can aid in visualizing mathematical models and concepts, helping students understand abstract concepts through interactive and engaging visual representations (Tjahyadi et al., 2023). Such visualizations could also be used for describing the process of the DT to better understand the real-time reflection of environmental changes that can be further used in various environmental studies.

Hsiao et al. (2022) introduced a cyber-physical co-existence environment for practical distance learning activities - CPE: "Co-existing Practical Environment" which contains a "Holographic Wearable Device" for behavior sensing and vision sharing, a cloud "Digital Twin Model" database for expert variable correction in real time, and a discussion interface.

Georgakopoulos et al. (2023) proposes remote laboratory courses based on the educational principles for sustainable development. The benefits of this strategy include helping students acquire critical thinking, problem solving, and collaborative competencies. DT leads to increase student motivation (Terkaj et al., 2024; Acker et al., 2023; Chamorro-Atalaya et al., 2024), encourage self-responsibility for learning (Bunse et al., 2022; Chamorro-Atalaya et al., 2024), facilitate peer learning (Bunse et al., 2022), and improve content delivery (Terkaj et al., 2024; Acker et al., 2023), demonstration ease (Lee et al., 2023), and student assessment (Lee et al., 2023; Mourtzis et al., 2023).

5.3 Personalized Learning Environments

Personalized learning is a process in which the method of learning and instructions are adjusted or personalized to the learner's requirements (Mitra, 2023). AI-driven technology has the potential to revolutionize education by providing personalized learning experiences (Dhananjaya et al., 2024). Digital twins could contribute to medical education and improve diagnostics of diverse forms of disease where there is a need for personalized treatment strategies in healthcare (Peshkova et al., 2023).

Intelligence (2023) explores the use of DTs technology in music education, focusing on improving teaching quality through the integration of real and virtual teaching spaces and online learning data analytics. It further suggests that a well-designed DT system can enhance students' interest in music learning by facilitating interaction and providing real-time feedback. Chatbots and virtual assistants can enhance student education by providing personalized assistance, answering questions, offering feedback, and suggesting learning resources (Dhananjaya et al., 2024). This demonstrates how DT can be tailored to individual students, maximizing their potential.

5.4 Economic Alternatives

In robotic education, the open-source omnidirectional mobile robot platform (ROBOTONT) can offer professional tools for robotics education and provide researchers a portable platform for validating scientific results (Raudmäe et al., 2023), providing a DT based economical alternative for conducting research when access to a physical platform is unavailable (Acker et al., 2023; Eriksson et al., 2022; Flaga et al., 2022).

Acker et al. (2023) offer a way for secondary school students to study Industry 4.0 technologies, build ICT skills, and establish a practical learning environment by utilizing a low-cost digital twin prototype. The prototype enables STEM skills development and critical thinking through simulations, testing, and implementation of simple algorithms, facilitating real-time data exchange between simulation environments and robotic systems.

Zangl et al. (2023) are introducing a low-cost robot platform that can be used to handle a wide range of measurement science and sensor subjects, as well as machine learning, actuators, and mechanics. The 3D printed chassis may be outfitted with various sensors for environmental perception while being adaptable to a variety of embedded computer platforms.

To present principles of robot simulation and realization approaches in a hands-on manner, the table-top robot is also available as a digital twin. Xi and Cong (2022) describe how Tianjin University's field trip for a measured survey of built heritage was replaced with remote solutions that included on-site data gathering, post-processing, online instruction, observation, modeling, and delivery. Čech and Vosáhlo (2022) present a cost-effective approach for teaching digital twins in control engineering education, demonstrating their application using a gantry crane simulator.

Komninos and Tsigkas (2022) describe usage of DT to give children the ability to interact with the natural environment from the classrooms, which consists of a smart birdhouse and an electronic DT where the smart birdhouse is placed in a natural setting to collect atmospheric data, such as humidity and temperature measurements, as well as record sounds and images of potential birds. At the same time, the collected data will be available to the end user via a dashboard, which plays the acquired music or images.

5.5 Develop Skills

Digital twin technology can promote development of multidisciplinary skills (Acker et al., 2023; Bunse et al., 2022; Flaga et al., 2022; Lee et al., 2023; Samak et al., 2023), thus preparing students to cope with the future demands of the industry (Hazrat et al., 2023). Some authors propose a framework to prepare students for the development and application of Industry 5.0 technologies (Ruppert et al., 2022; Acker et al., 2023; Eriksson et al., 2022; Lee et al., 2023; Tjahyadi et al., 2023). To better incorporate the increasing competency requirements of the working world 4.0 Boettcher et al. (2023) employed a real-world scenario (RWS) to address the ambiguous problem-solving assignments in W4.0. DT concept could also be used for smart grid security studies, allowing users to gain experience testing attacks and countermeasures in a controlled setting (Kandasamy et al., 2022). Mathur (2023) highlights its utility in research, education, and training in critical infrastructure defense. It could be used in various fields to improve not only the mental but also physical abilities of students. For example, Liu and Jiang (2022) explore the application of DT in physical education teaching practice, involving 25 participants in an exercise detection and analysis experiment, aiming to design a platform for efficient information collection and processing.

On the other hand, Vrysouli et al. (2023) is introducing ideas of DT and sustainability in the vocational program in the sector of construction works, structured environment and architectural design. Goppold et al. (2022) presents a learning system based on learning from errors. In a technical proof-of-concept, DTs are used to simulate and see the harmful consequences of erroneous acts.

6 Future Directions

While existing studies discuss the benefits of digital twins in various educational contexts, there is a gap in a comprehensive, comparative analysis of how these benefits vary across different educational levels (elementary, secondary, and higher education). In addition, ethical implications and privacy concerns associated with the use of digital twins in education are not thoroughly explored. This includes issues related to data security, consent, and the potential misuse of personal data. There is a lack of adequate education about the digital twin concept, which is why efforts should be made to develop cost-effective teaching strategies to bridge the gap between education, research, and industrial practice (Čech and Vosáhlo, 2022). Acker et al. (2023) and Orsolits et al. (2022) also agree that cost-effective solutions should be pursued to improve robotics education, which will be critical in meeting future industry demand. Not only for its cost-effectiveness, it is also necessary for simulations that otherwise would not be possible to perform like offensive security testing (Kandasamy et al., 2022). DT has often been associated with the IoT, but visual sensor technology is now increasingly being explored to collect data without need for wearable devices (Liu and Jiang, 2022). This new perspective on the digital twin will raise various open questions, including the privacy threat it might bring.

7 Conclusions

The use of digital twin technology has yielded several benefits in a wide range of fields, including STEM education, distance learning, vocational training, and other fields including music, physical education, internet of things and environmental education. The advantages of DT are most evident in STEM education, particularly in the areas of robotics and engineering, where it acts as a mold for conducting a variety of experiments. As an applicable economic alternative for developing multidisciplinary competencies, it has gained popularity and is employed for both virtual laboratory enhancement and diverse simulation purposes. It helps to create personalized learning environments in which the instructions and learning strategy are customized to meet the needs of each individual student.

While there are educational benefits of digital twins, they should be taken with caution. The existing studies do not fully address ethical implications and privacy concerns, such as data security, permission, and the use of personal data. Future studies should therefore examine the responsible use of digital twin technology, particularly when combined with other emerging technologies like augmented reality and artificial intelligence tools. The digital twin could be a useful tool for creating future learning environments with a focus on bridging the gap between academics and industry because of the advantages it provides. For this reason, digital twin-based virtual environments may have an impact on future directions for educational practice and policy.

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